ACCELERATION OF IONS BY INTENSE MEV ELECTRON BEAMS

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I. Introduction

The technology for the production[1] of intense MEV electron beams involves well known components. High voltage is usually produced by Marx generators or a Van de Graaff accelerator. A transmission line (Blumlein) is charged to high voltage and forms a pulse. The pulse is applied to a low impedance field emission diode that has a thin foil anode. Accelerated electrons pass through the anode foil into a drift tube that usually has a metallic surface conductor which may carry all or part of the return current. The type of gas and pressure in the drift tube can be controlled and beam propagation over several meters has been observed for gas pressures from 50 microns to about 1500 microns.

Energetic ions were first observed by S. Graybill and J. Uglum [2]. The operating conditions were mean electron energy 1,3 MeV, beam current $I \simeq 50\,000$ amperes, and pulse duration $T \cong 40$ nanosec. Ions were observed by deflecting electrons at the end of the drift tube with 3 Kgauss magnetic field and measuring the number of ions that reach an ion current probe. Ion energy was determined by time of flight analysis. Ion energies observed were 5 MeV for protons and deuterons, 9 MeV for Helium and 20 MeV for Nitrogen. A further check was made by observing Be^9 (x,n) reactions for protons, deuterons and helium. The ion current was generally a pulse of $3-10$ nanosec. in width. The total number of ions accelerated corresponds to about 10 amperes over 50 nanoseconds, or one ion accelerated for 5×10^3 electrons. The ion energy was insensitive to background gas pressure, but the total number of ions is greatest for $p \sim 100-200$ microns and drops sharply at higher or lower pressures.

Using similar measuring techniques G. Yonas [3] has observed 5 MeV ions with 200 k-amperes of 0.56 MeV electrons.

Energetic particles have been observed with photographic emulsions by M. Friedman and A Kuckes [4]. With a 60 k-ampere 0.35 MeV electron beam, parallel tracks in the emulsion have been observed that would correspond to protons with energies greater than 10 MeV. This data is not very reproducible.

At present the experimental data is quite limited, has a great deal of scatter and is not very reproducible in many cases. It is, nevertheless, sufficiently credible to stimulate a serious effort to determine the mechanism of acceleration.

In most of existing charged particle accelerators the electric field is created externally. A number of proposals for accelerators based on internally created fields have been advanced by V. I. Veksler[5]. One of these ideas involves the Cerenkov radiation of plasma waves by ion bunches. This idea has been applied to the present problem by B. J. Eastlund and J. M. Wachtel[6]. In the frame where the beam electrons are at rest the ions radiate plasma waves and lose energy at the rate

$$\frac{dW}{dt} = \frac{e^2\omega_p^2}{V} \ln \frac{V}{V_{th}} \tag{1}$$

where $\omega_p = \sqrt{\frac{4\pi ne^2}{m}}$ is the beam plasma frequency, V is the velocity of ions in this frame and the electrons are assumed to have a Maxwell distribution with thermal velocity V_{th}. Assuming protons and a beam density $n=10^{12}$ of 1 MeV mean energy electrons

$$\frac{dW}{dt} = 10^{-10} \text{ MeV/nanosec.} \tag{2}$$

For a single particle the effect is negligible. However, if a bunch of N ions radiates coherently the rate is increased by a factor N. Wachtel and Eastlund assume $N \simeq n(V_{th}/\omega_p)^3$. With a sufficiently large beam temperature e.g. $V_{th} \sim 10^{10}$ cm/sec. the rate of deceleration of ions could be large i.e. $dW/dt \sim 2$MeV/nanosec. and one could account for the observed energies. The ion bunch decelerates in the beam-frame and therefore accelerates in the laboratory frame. In $\gamma_0 T \sim 150$ nanosec a proton would lose about 300 MeV in the beam frame which corresponds to about 10 MeV in the laboratory frame. At present both the calculations and the experimental data are too crude to come to any definite conclusions about this mechanism.

Considering the fact that the electron beam passes through a neutral gas there must be regions of the beam that are only partially neutralized and large electric fields can be created by the space charge of the beam. Several mechanisms based on such considerations have been discussed previously [7]. In the balance of this paper we shall consider a particular form of this mechanism that is appropriate to the experimental conditions for which energetic ions have been observed.

II Theory of the Space Charge Wave

Assume that electrons are launched from the anode foil into the drift tube with a velocity $V_+=\beta c$ and kinetic energy $(\gamma_0-1)mc^2$ where $\gamma_0=(1-\beta^2)^{-1/2}$. According to a one dimensional analysis a space charge will be set up as indicated in Fig. 1.

For a mono-energetic beam a potential hill must be created for electrons that is sufficient to reflect them. Therefore, $\Phi_0=-(\gamma_0-1)mc^2/e$. It will be established over a scale distance $L\simeq c/\omega_p$ so that the electric field at the anode will be $E_0\simeq-\Phi_0/L$. The electron density will become weakly infinite at $x=L$ because electrons near $x=L$ have a very low velocity and spend a great deal of time in this vicinity. Also $n(x)=0$ for $x>L$. The time scale for setting up the potential hill is ω_p^{-1} where $\omega_p^2=4\pi n_b e^2/m$. The detailed shape of $n(x)$ near $x=L$ will take a very long time to establish. However, it is relatively unimportant and the approximation $n(x)=n_b$ is adequate for most purposes. We assume typical data $\gamma_0\simeq2$ corresponding to 1 MeV electrons, $n_b=10^{12}cm^{-3}$ in which case $\omega_p\simeq3\times10^{10}sec^{-1}$, $L\simeq1cm$ and $E_0\simeq1$ MeV/cm.

If in the drift tube there is a neutral gas of density "n_0" the beam electrons will produce ions and secondary low energy electrons on a time scale $\tau_I\simeq\frac{1}{n_0\langle\sigma V\rangle}$ · $\langle\sigma V\rangle$ is not simple to estimate since V varies from $V_+=\beta c$ to zero. σV for Hydrogen varies from 8×10^{-8} at 100 ev to 4×10^{-9} at 500 kev. In addition the further ionization of the secondary electrons must be considered. However, since n_0 can be easily changed over several orders of magnitude, it is clear that τ_I can be adjusted by varying the background pressure. We shall assume $\tau_I\simeq10$ nanosec. Considering the fact that the beam is cylindrical and has a finite radius "R" there will be a radial electric field that will expell the secondary electrons on a time scale $\tau_e\simeq(R/L)\omega_p^{-1}$ which is a few plasma oscillation periods. It is thus clear that $\tau_I\gg\tau_e$. As the space charge becomes neutralized on a time scale $\tau_N=\tau_I+\tau_e$ the beam electrons can move forward and create a new space charge structure. The space charge structure will advance through the background gas with a speed $V_p\simeq\frac{c}{\omega_p\tau_N}\ll V_+$. In a frame of reference moving with velocity V_p the structure will be as indicated in Fig. 2.

We define the length L_I such that

$$\int_0^L dx\ n_I(x)=n_b L_I$$

and $L_I\sim c/\omega_p$ from the previous considerations. Since

$$\frac{d^2\Phi}{dx^2}\simeq4\pi e[n_b-n_I(x)], \tag{3}$$

the electric field at $x=0$ is

$$E_0 \simeq 4\pi e n_b (L - L_I) \tag{4}$$

L is defined such that at $x=L$, $d\Phi/dx=0$, $\Phi=\Phi_0$.
Therefore $L \simeq \sqrt{2} L_I$.

Ions are trapped in a moving potential well so that they have an energy

$$\frac{1}{2} M V_p^2 = \frac{1}{4} (M/m) \ (\omega_p \tau_N)^{-2} \mathrm{MeV} \tag{5}$$

$$\simeq 50 \ \text{kev for protons.}$$

For various reasons there should be some ionization ahead of the moving well. They are as follows

I) Radiation produced when the beam passes through the anode foil would ionize the neutral gas ahead of the well.

II) Scattering in the anode foil should give the beam electrons an effective temperature so that some energetic electrons can pass over the potential hill.

III) The current pulse does not have an infinitely steep front, but rises to the full value in about 5—10 nanosec.

As the density of ions and low energy electrons grows ahead of the moving well the time τ_N for the well to move a distance L must shorten from $\tau_N = \tau_I + \tau_e$ to $\tau_e \simeq \omega_p^{-1}$ in which case the moving well must accelerate. When $\tau_I \sim 0$ and the only process required for neutralization of the space charge is radial expulsion of secondary electrons, the velocity of the well must approach $V_p \simeq c$. In order that the trapped ions be retained in the well the acceleration must not be too rapid. The criterion for this is

$$\frac{d}{dt} \frac{M V_p}{\sqrt{1 - V_p^2/c^2}} = \frac{M \dot{V}_p}{(1 - V_p^2/c^2)^{3/2}} < e_I E_0 \tag{6}$$

To estimate the acceleration of the potential well we assume n_b^* electrons/cc ahead of the well so that the ion density grows like $n_I = n_b^* t/\tau_I$. The number of excess ions available for neutralizing the advancing space charge is

$$\frac{n_b^*}{\tau_I}(t - \tau_I).$$

Therefore the time to produce the necessary ionization will be reduced to

$$\tau_I' = \frac{\left[n_b - \dfrac{n_b^*}{\tau_I} (t - \tau_I) \right]}{n_b/\tau_I}$$

$$= \tau_I \left[1 - \frac{n_b^*}{n_b} \left(\frac{t}{\tau_I} - 1 \right) \right]. \tag{7}$$

Since

$$V_p(t) \simeq \frac{L}{\tau_N} = \frac{L}{\tau_I' + \tau_e'},$$

$$\dot{V}_p \simeq \frac{L}{\tau_N'} (n_b^*/n_b). \tag{8}$$

From Eqs. (4) and (8) the criterion of Eq. (6) becomes

$$(\omega_p \tau_N)^2 > \frac{e}{e_I} \frac{M\gamma_p^3}{m} \frac{n_b^*}{n_b}. \tag{9}$$

On the basis of these equations the present observations could be accounted for. The maximum ion energy that can be attained without violating Eq. (9) is

$$E_I = \frac{MV_p^2}{2} \simeq \frac{n_b}{n_b^*} \mathrm{MeV}.$$

Assuming $n_b/n_b^* = 5$ the time to attain this energy is

$$T \simeq \frac{n_b}{n_b^*} \tau_I = 50 \text{ nanosec.}$$

The total numbe*r* of ions accelerated per beam electron is

$$\frac{L_I}{V_+ T} = 0.7 \times 10^{-4}$$

which corresponds to an average current of 3.5 amperes of protons. If ions other than protons are accelerated, the maximum energy that can be obtained assuming the ions are stripped is

$$E_I = \frac{n_b}{n_b^*} Z \text{ MeV}, \tag{10}$$

where Z is the atomic number. The ions should be essentially monoenergetic as observed in some of the experiments. The pulse width for the ion current should be very short

$$\Delta t \sim c/\omega_p V_p \simeq \tau_N = 0.3 \text{ nanosec} \tag{11}$$

for protons. However, if the ions are separated from the electron beam with a magnetic field, the ions will spread under the influence of their space charge and the observed pulse width will be mainly determined by the conditions of observation.

The distance over which the acceleration takes place is

$$L_A = I\int_{t=0}^{t=\frac{n_b}{n_b^*}\tau_I} \frac{dt}{\tau_I\left[1-\frac{n_b^*}{n_b}\left(\frac{t}{\tau_I}-1\right)\right]}$$

$$= L\frac{n_b}{n_b^*}\log\left(1+\frac{n_b}{n_b^*}\right) \cong 9 \text{ cm}. \qquad (12)$$

It is often observed that intense MeV electron beams develop gross oscillations. The oscillation may start near the anode foil or develop further downstream. There are two likely causes for these oscillations

I) The beam is launched off axis due to cathode emission irregularities or asymmetry in the application of voltage from the Blumlein. As long as there is a return conductor, image forces change the direction of the beam so that it propagated in the general direction of the axis, but with oscillations.

II) Instabilities such as the "Firehose" instability may develop.

If oscillations develop in the first 9 cm where the ion acceleration takes place, the ions will usually not be able to follow the oscillations. The electrons follow the oscillations. However, this requires a much smaller electric field for the centripetal force than the ions would require after they have accelerated to an energy in excess of the electron energy. If the ions fail to follow the gross oscillations either the acceleration will cease or the ions will simply hit the walls. Since the development of oscillations, particularly in the first 9 cm is at present not under control, substantial variations and lack of reproducibility are to be expected in the experimental data.

Conclusions

The theory of the space charge wave is able to account for most of the observations to date. Since the experimental data to date has some uncertainties, it is not completely clear whether we have developed a useful principle for accelerators or accomplished an exercise in agility. Assuming the former is the case some conclusions may be drawn and some suggestions for improved performance are apparent.

1) Since the space charge wave has an electric field of $E_0 \sim \sim \frac{(\gamma_0-1)mc^2}{c/\omega_p} \cong 1$ MeV/cm at the location of the ions it should be possible to accelerate ions to 100 MeV in 1 meter if the acceleration is suitably controlled so that Eq. (6) is always satisfied. We have so far discussed the most likely cause for acceleration in terms of present experiments. It is clear that the ionization in front of the space charge wave could be controlled better to optimize the acceleration of the space charge wave.

2) The oscillations in the beam can be reduced and probably eliminated by placing the field emission diode and drift tube in a strong

longitudinal guide field. It has been demonstrated experimentally[9] that with a guide field of 10 kilogauss, the diode performance is substantially improved. i. e. the beam is launched in the direction of the field, is much more uniform and reproducible. Improved propagation characteristics have also been observed at low background pressures. In addition to improving the geometry, the guide field can inhibit instability such as the "Firehose" instability.

3) It should be possible to accelerate ions to an energy of $\sim$ $\sim(\gamma_0-1)Mc^2$, since the space charge wave should eventually reach the velocity of the beam electrons. The present calculations treat the ions non-relativistically so that some refinements need to be made. It is likely that the beam pulse length T would be too long to be practical. However, something like $(\gamma_0-1)Mc^2/2$ can probably be achieved with a reasonable pulse length T.

Acknowledgements

I would like to thank Professors H. Fleischmann and R. Sudan for critical discussion and Drs. S. Graybill, J. Uglum and G. Yonas for the opportunity to see their experimental data prior to publication.

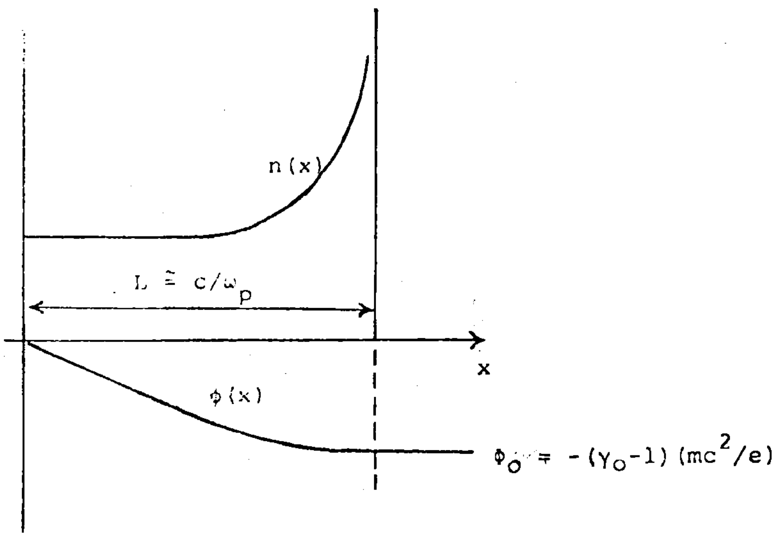

Fig. 1. Electron Density and Potential for an Electron Beam Launched into Vacuum

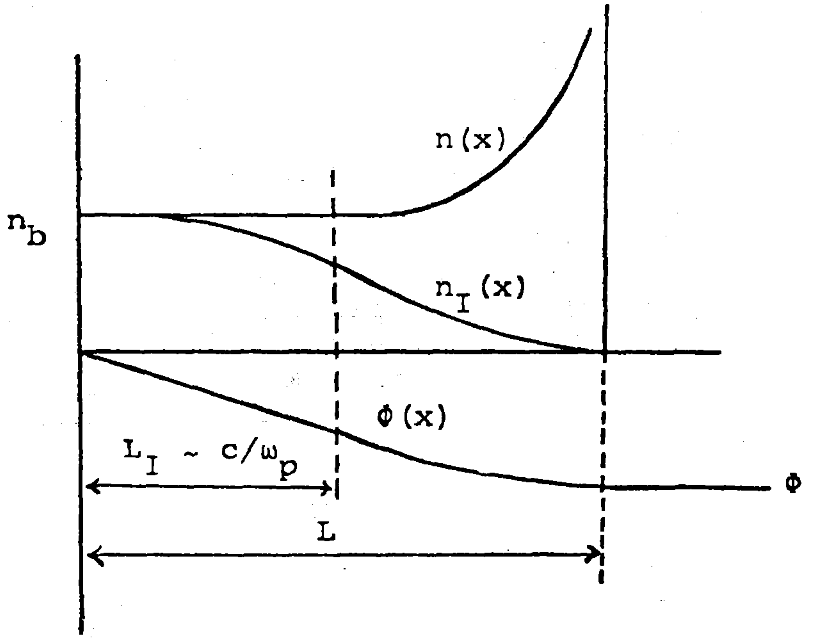

Fig 2. Particle Densities and Potential for an Electron Beam Moving through an Initially Neutral Gas

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